Intersil

Analysis and Simulation of Overlapped Frequency Hopping Channels

(ET Docket 99-231)

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8/30/99

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Abstract

The effect of using overlapping channels for wide band frequency hopping (WBFH) systems as proposed in a recent Commission Notice of Proposed Rule Making (NPRM ET Docket 99-231) is studied. Measured data indicating that the use of such channels will actually increase interference among WBFH systems is presented. Basic principles of non-coherent frequency shift keyed (FSK) modulation/demodulation are reviewed. A mathematical model of an FSK receiver employing a limiter/discriminator type receiver is described. Simulation results demonstrating that interference enhancement is an inevitable consequence of overlapping channels are presented. It is also shown that these effects are due to a well known property of FM demodulation. Adverse impacts on system performance which will result from the use of overlapped channels are explained. Finally, implications for systems employing other types of modulation capable of high spectral efficiency, such as 16QAM are discussed.

1.0 Summary

Intersil Corporation opposes the proposed changes regarding operation of Frequency Hopped Spread Spectrum (FHSS) radios under Part 15.247 of the Commission's rules as described in a recent NPRM (ET Docket 99-231). The proposed changes would allow the use of channels having widths of up to 5 MHz to accommodate higher data rates for FHSS systems. As a result of increased width, FHSS channels will overlap to a large degree as shown in Figure 1.0-1.

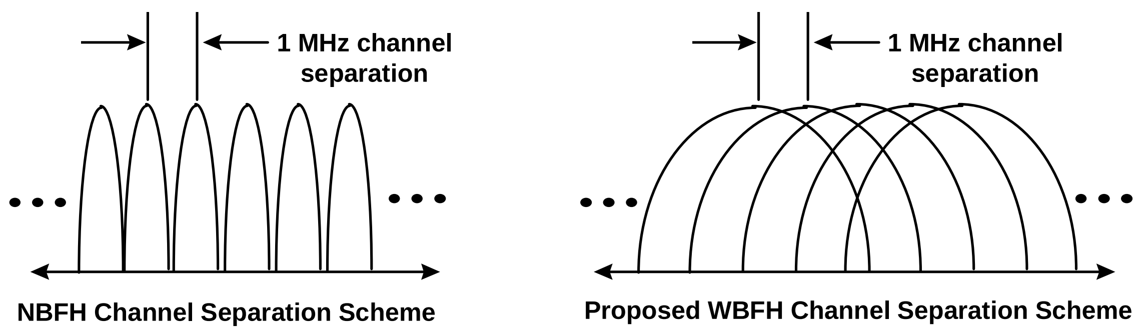


Figure 3.0-2 Channel Separation Schemes for NBFH and WBFH Systems

The use of overlapping channels was proposed by HomeRF in its petition for rule making in order to overcome FCC objections to an earlier proposal by Symbol (Rule Making 8608). In that proposal, Symbol sought to both widen FHSS occupied channels, and to reduce the minimum number of channels from 75 to 15. In its NPRM and Order (ET Docket 96-8), the Commission indicated that reducing the number of FHSS channels would result in increased interference to other users.

At first glance, it would appear that the severity of interference from a partially overlapped channel *decreases* as frequency separation *increases*. In other words, one would expect the effects of an interferor centered some fraction of a channel width away from the desired signal to be less severe than an equal strength co-channel interferor. In fact, the interference in this situation is actually *worse*. The data presented in this paper demonstrates that the use of overlapping channels will result in still higher levels of interference to other users. Due to the increased frequency and severity of collisions among WBFH systems, retransmissions will compound the aforementioned effects. The current proposal therefore results in higher levels of interference to other users of the 2.45 GHz ISM band than the earlier Symbol proposal which was rejected by the Commission.

In an earlier submission to the Commission [1], test data was presented which indicated that interference from a partially overlapped channel was actually worse than for either co-channel interference (CCI) or adjacent channel interference (ACI). A heuristic explanation for this effect was presented. Since that time, a more detailed explanation for the interference-enhancing effects of overlapping channels has been developed.

It is a well-established fact that FM demodulation *enhances noise and interference in proportion to the square of the frequency separation from the desired signal.* Use of overlapping FHSS channels will result in interfering signals which are offset in frequency from the desired signal, yet still fall within the receiver passband. Simulations have shown that differential phase distortion occurs when an interfering FHSS signal is combined with the desired signal. Since this is due to an interfering signal which falls within the passband of the desired signal, no amount of filtering can overcome its harmful effects.

For a given Signal-to-Interference (SIR) ratio, the degree of phase distortion increases as a function of frequency separation between the desired and undesired signals. Therefore, Bit Error Rate (BER) increases as channel separation increases. This effect subsides only when the frequency separation of the two signals becomes large enough such that the receiver Intermediate Frequency (IF) filter can begin to suppress the undesired signal. This requires a frequency separation typically of about one channel width (ACI).

For the purpose of this discussion, CCI is interference which has the same center frequency as the desired signal. ACI is interference which is centered in frequency exactly one channel width away from the desired signal. Interference from partially overlapped channels is more severe than either CCI or ACI precisely because it is offset in frequency from the desired signal, but not sufficiently so such that the IF filter can suppress it. This represents a “worst case” situation for FHSS radios.

Finally, it must be pointed out that there is nothing in the proposed rule changes which will require manufacturers to employ FSK modulation. However, nearly all commercially available FHSS systems do, in fact, use this form of modulation. Moreover, in a February 25th, 1999 submission to the Office of Engineering and Technology in this proceeding [2], HomeRF made specific mention of its intention to use FSK modulation for WBFH applications. However, even if other forms of modulation such as 16 QAM are used, it is entirely reasonable to assume that the phase distortion resulting from overlapped channels will cause similarly destructive effects.

2.0 Test Data

In an earlier submission [1] to the Office of Engineering and Technology (OET) in this same proceeding, test data showing the destructive effects of overlapping channels was presented. For the sake of continuity, this data is briefly summarized. Figure 2.0-1 shows results of receiver desensitization testing for a 4FSK FHSS radio. Receiver desensitization is a measure of the ability of a receiver to reject an interfering signal from a transmitter which uses the same modulation technique, but with an uncorrelated data sequence.

The figure of merit is the level of the interfering signal required to cause the BER of the desired signal to exceed a predetermined threshold. The BER threshold for the data shown in Figure 2.0-1 is 10^{-5}. For each value of frequency offset, the interference level is increased until the BER for the desired signal reaches 10^{-5}. Note that, in general, as the frequency separation between the desired and interfering signals increases, the level of interference required to cause receiver failure also increases. However, this is not the case for those frequencies which are less than 1 MHz away from band center of the desired signal.

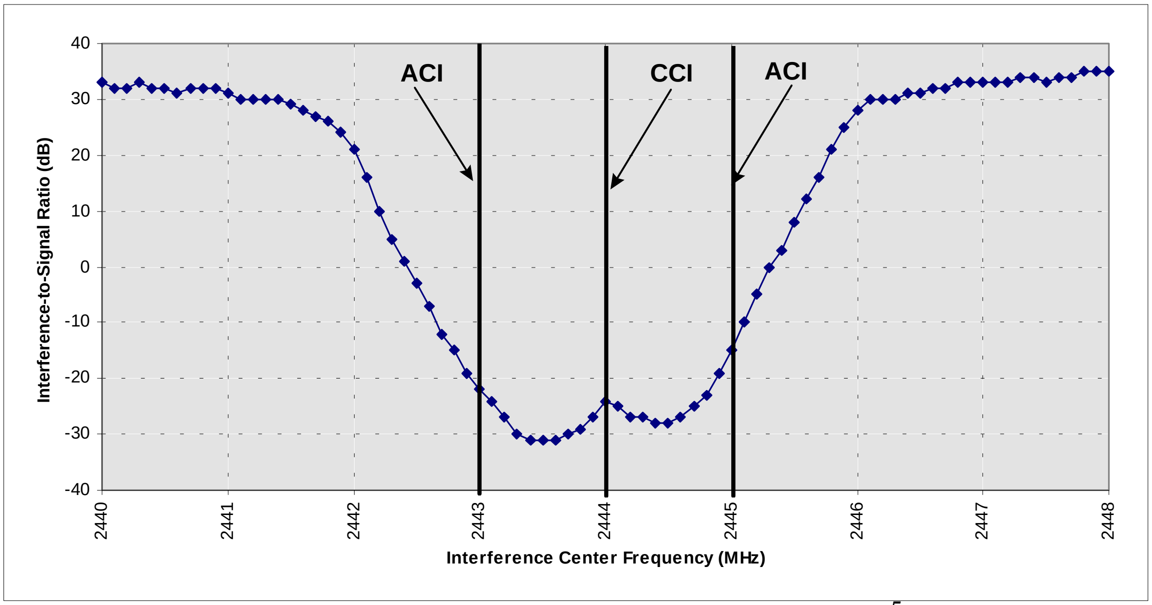


Figure 2.0-1 Rx Desensitization Data for 4FSK FHSS Radio (10^{-5} BER Threshold)

Interference centered at frequencies within 1 MHz of 2444 MHz corresponds to overlapping channels. Note that receiver desensitization is worse than either CCI (interference centered at 2444 MHz) or ACI (interference centered at 2445 MHz or 2443 MHz). Although this data was generated using 2 Mbps 4FSK radios having a 1 MHz channel width, the results are completely scalable to either 6 Mbps 4FSK radios having 3 MHz wide channels or 10 Mbps 4FSK radios having 5 MHz wide channels. The modulation index (h = 0.15), effective bandwidth of the pulse shaping filter (BT = 0.5), and spectral mask requirements (-20 dB at band edge) are identical for both NBFH and WBFH systems analyzed in this paper.

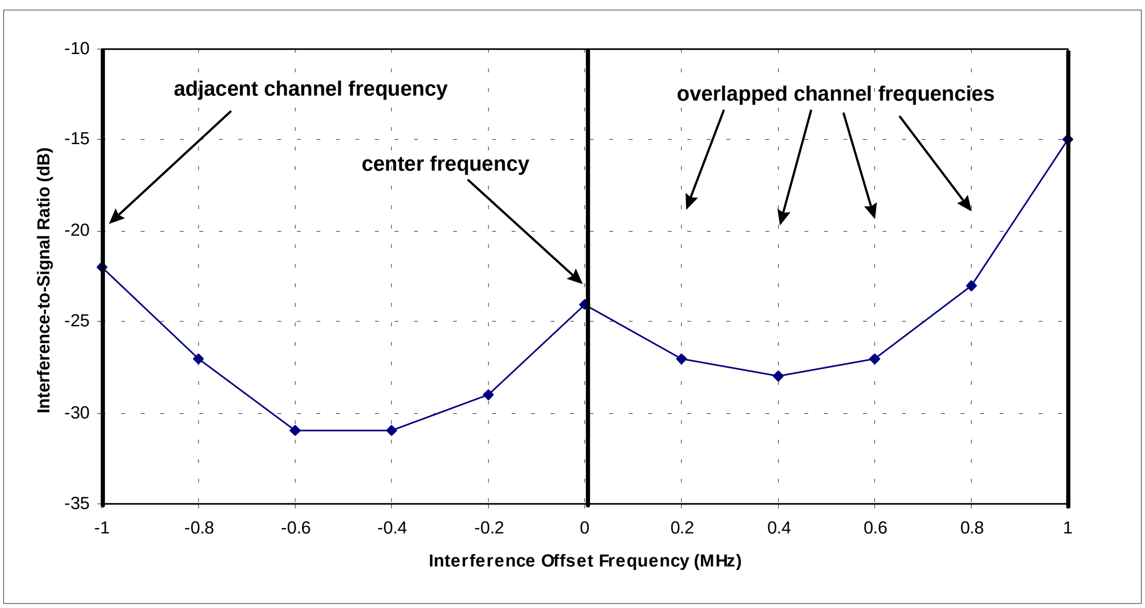


Figure 2.0-2 Subset of Rx Desensitization Data (10^{-5} BER Threshold) Demonstrates Interference is Most Severe from Partially Overlapped Channels

Figure 2.0-2 shows a subset of the receiver desensitization data. The data is plotted as a function of normalized channel offset. A frequency offset of 0 MHz corresponds to co-channel interference. The level of co-channel interference required to cause receiver failure is -24 dB. A frequency offset of +/-1 MHz represents the effect of adjacent channel interference. These are the nearest non-overlapping channels. Of particular interest is the receiver desensitization data for the frequencies lying between 0 MHz and +1 MHz offset and between 0 MHz and -1 MHz offset. These data points correspond to the effects of interference from partially overlapped channels. Note that these levels are actually worse (by up to 7 dB) than either co-channel interference or adjacent channel interference.

If overlapped channels were not allowed, an interfering signal would be forced to hop to an adjacent channel, or directly into the same channel as the desired signal. In either case, the resulting level of interference is lower than if the interfering signal is permitted to occupy a partially overlapped channel. Aside from the increase in mutual interference that WBFH radios will suffer from, the resulting increased retransmission rate will adversely impact other users of the spectrum. Therefore, while the use of overlapping channels have been proposed as a means of *reducing* interference, the end result is actually an *increase in the level of interference*, both for WBFH radios and existing users of the spectrum.

3.0 Modeling a Non-Coherent FSK Communication Link

The data presented in Section 2.0 is interesting, but it does not offer a rigorous explanation of why interference from partially overlapped channels appears to be so severe. In the absence of such an explanation, the effect could be dismissed as being due to the particular radio implementation under study, or perhaps to some anomaly in the test procedure. To gain better insight into this situation, computer models were developed to enable controlled simulation of the interaction of two overlapping FSK signals. The models are equivalent complex baseband representations of an FSK transmitter/receiver pair. The use of equivalent complex baseband models results in no loss of simulation accuracy or mathematical rigor, and renders much simpler computer code. Programming and simulation were done in MATLAB.

3.1 Non-Coherent FSK Transmitter

A simplified block diagram of the transmitter is shown in Figure 3.1-1. The transmitter accepts a binary data stream and maps bit pairs to 4-level PAM symbols. This is followed by a Gaussian pulse shaping filter with an effective filter bandwidth (BT) of 0.5. The pulse shaping filter is required to ensure that the transmitted waveform is –20 dB at the band edge relative to the peak of transmitted power at band center, as required in Section 15.247 of the Commission's rules.

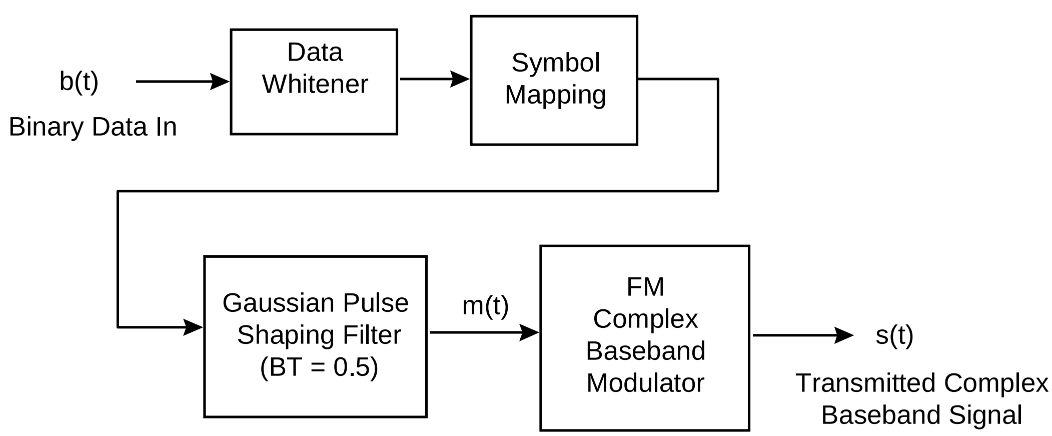


Figure 3.1-1 Equivalent Baseband Model of a Non-Coherent 4FSK Transmitter

The Power Spectral Density (PSD) of a transmitted signal s(t) is shown in Figure 3.1-2. The signal is that of a 4FSK radio operating at 2 Mbps (1 M symbols/sec). Note that the PSD is triangular in shape (on a decibel scale) and is -20 at band edge relative to peak power.

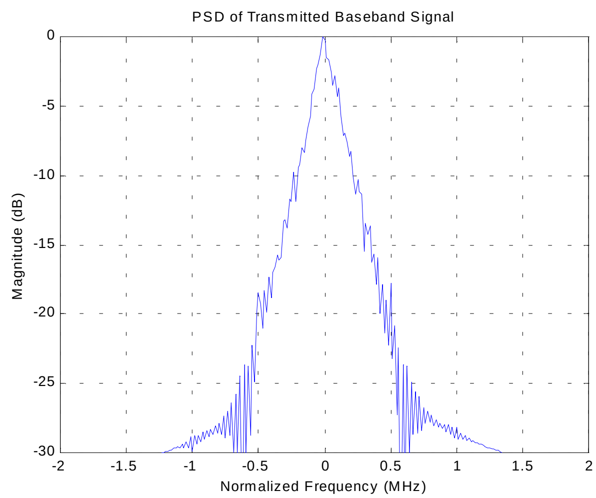


Figure 3.1-2 PSD of Transmitted 4FSK Signal

The instantaneous phase of a frequency modulated (FM) signal can be mathematically represented as shown in Equation (1) below [3]. The modulation constant (k_f) is chosen such that the 4 level PAM symbols are converted to the carrier deviation frequencies described in Section 14.7.2 of the IEEE 802.11 Standard [4].

$$\theta(t) = k_f \int_0^t m(\tau)d\tau + \theta_o \qquad (1)$$

where:

$\theta(t)$	=	instantaneous phase
k_f	=	modulation constant
$m(t)$	=	Gaussian filtered 4 level PAM signal
θ_o	=	initial phase deviation at time t_o (arbitrarily set to 0)

The instantaneous frequency, *f(t)*, generated by the modulator is the time derivative of the instantaneous phase. Taking the derivative of Equation (1) with respect to time, it becomes apparent that the frequency of the modulator output signal is proportional to the modulator input voltage, m(t).

$$f(t) = d\,\theta(t)/dt = k_f\, m(t) \qquad (2)$$

Since the resulting signal is a complex baseband representation, the "carrier" frequency is 0 Hz. Thus, both positive and negative frequency deviations are possible. As stated above, the magnitude of the instantaneous frequency deviation is proportional to the magnitude of the modulator input signal, m(t). The modulator output, s(t), can be visualized in the form of a rotating vector as shown in Figure 3.1-3. The *rate of rotation* is proportional to the instantaneous amplitude of m(t), and the *direction of rotation* indicates the polarity of m(t).

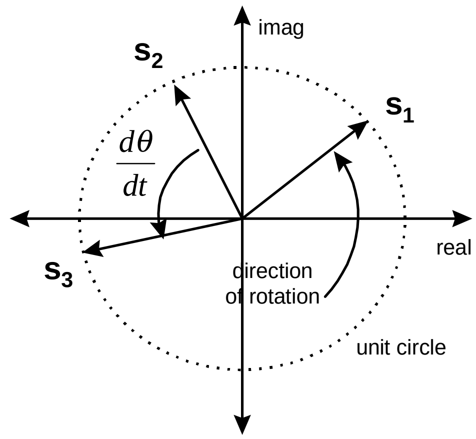


Figure 3.1-3 Rotating Phasor Representation of Transmitted Signal

3.2 Simplified Channel Model

A WBFH system would be very susceptible to multipath, even in a residential environment where the channel is supposedly more benign. However, this paper is focused on the effects of overlapping channels. Channel effects such as multipath are not analyzed in this paper. A simplified model is therefore adequate. In this case, the channel model is simply a means of linearly combining the desired signal, an interfering signal, and additive white Gaussian noise (AWGN), or some subset of these signals.

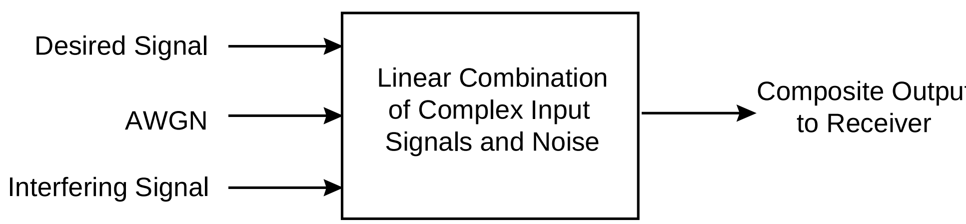


Figure 3.2-1 Simplified Channel Model

Again, a vector representation is a useful means of visualizing the process of linear combination of signals. Linear combination of a desired signal (S), interference (I), and noise (n) is depicted in Figure 3.2.2. Simulation results showing the PSD of a composite signal (C) are shown in Figure 3.2-3.

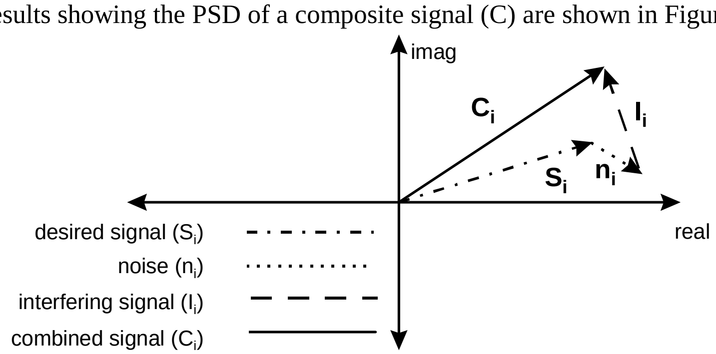
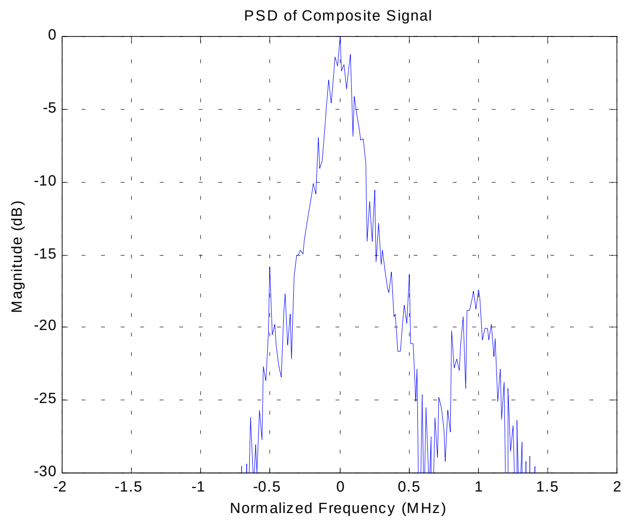


Figure 3.2-2 Linear Combination of Signal, Interference, and Noise

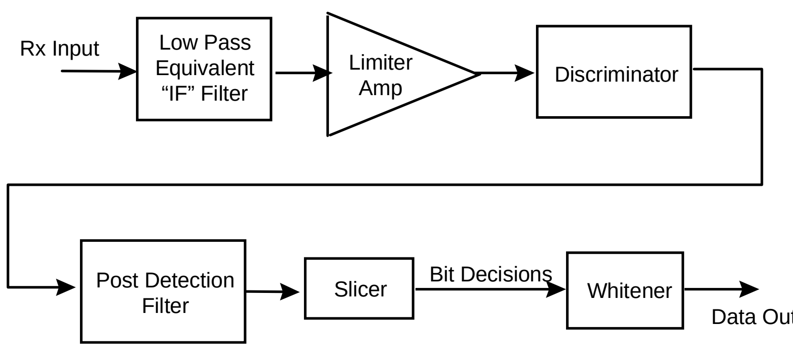


<u>Figure 3.2-3 Composite PSD of Signal, Offset Interference, and Noise</u>

3.3 Non-Coherent FSK Receiver

A limiter/discriminator receiver architecture is used almost without exception in commercially available FHSS systems. These systems include:

a. IEEE 802.11 FHSS
b. HomeRF (SWAP-CA)
c. Bluetooth
d. Symphony (Proxim)
e. Home Free (Diamond MM)



<u>Figure 3.3-1 Baseband Limiter/Disriminator Receiver</u>

A block diagram for a complex baseband FSK receiver featuring a limiter/discriminator architecture is shown in Figure 3.3-1. The received signal varies in amplitude and phase (Fig. 3.3-2a). The limiter function is simulated by projecting received signal vectors onto the unit circle as shown in Figure 3.3-2b. The received signal is thus modeled as a constant amplitude rotating phasor. Demodulation is performed by taking the time derivative of phase (Fig. 3.3-2c) to determine instantaneous received frequency.

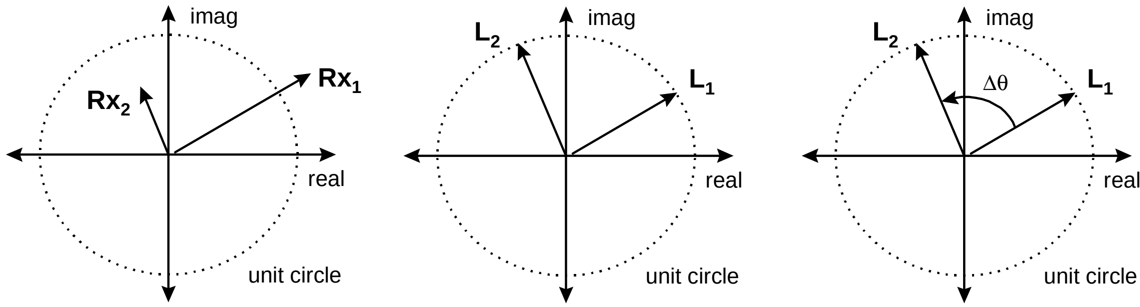


Figure 3.3-2a *Figure 3.3-2b* *Figure 3.3-2c*

Figure 3.3-2 Vector Representation of Limiter/Discriminator Demodulation

4.0 Simulation Results

Using the model described in Section 3, the receiver desensitization effect for overlapping channels shown in Figure 2.0-2 can be reproduced in simulation. The data shown in Figure 4.0-1 shows the effect of overlapping channels on receiver desensitization for a 10 Mbps 4FSK receiver. The interference and desired signals both employ 4FSK modulation @ 10 Mbps, but with independent and uncorrelated data streams. Both signals occupy a 5 MHz wide channel with the signal strength at -20 dB relative to peak at band edge.

For the simulation results shown below, the threshold for receiver failure is a BER of 10^{-3}. The receiver bit error threshold was raised to this level to reduce simulation time and in no way undermines the validity of the results. As a rule of thumb, the data sequence should be at least an order of magnitude larger than the inverse of the BER to ensure the sample is statistically valid. By reducing the BER threshold to 10^{-3}, data sequences of 10^4 bits are adequate. By comparison, simulation with a BER threshold of 10^{-5} would require data sequences of 10^6 bits.

$$\text{Simulation Data Sequence Length} \geq 10 / \text{BER} \qquad (3)$$

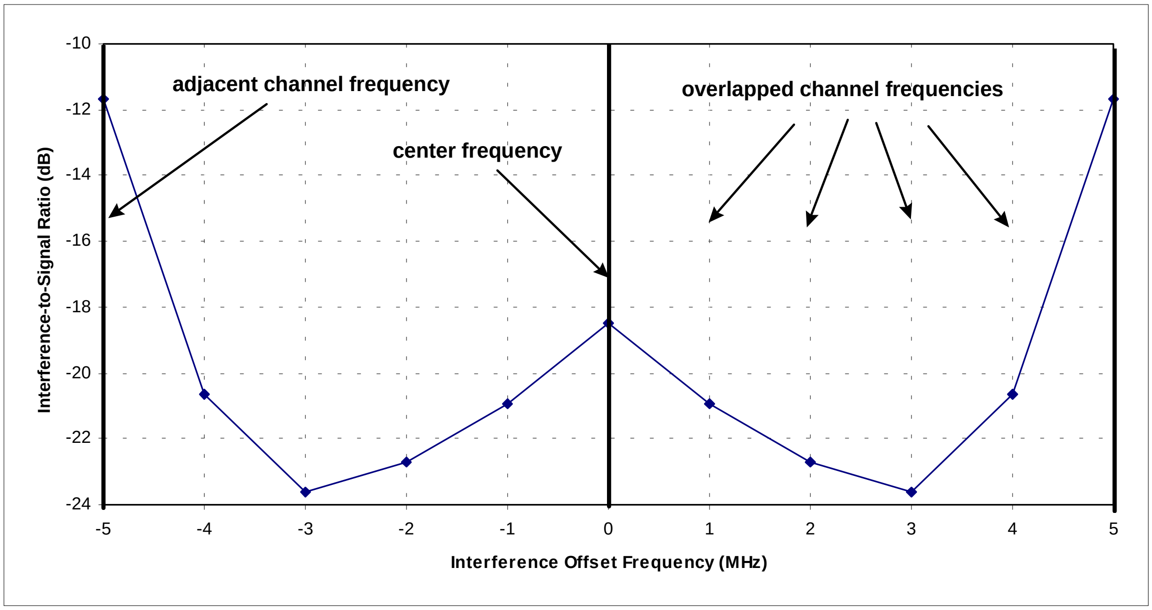


Figure 4.0-1 Simulated Rx Desense for Overlapping 5 MHz WBFH Channels

Note that the simulation results are perfectly symmetric about the center frequency of the desired signal. For the purpose of analyzing the effect of overlap channels, other effects such as Tx/Rx carrier offset, clock offset, and filter asymmetries have been removed. Note that the local maxima in the receiver desensitization curve at 0 Hz interference offset frequency is reproduced. So too are the local minima on either side of center frequency at a spacing of roughly half a channel width. Finally, note that receiver desense performance improves rapidly as the interference offset frequency approaches 5 MHz, or one channel width. In short, the interference situation is worse for overlapping channels than for either co-channel or adjacent channel interference. In this sense, the current WBFH proposal is technically inferior to the earlier WBFH proposal put forward by Symbol in 1994.

Simulation results are in excellent agreement with measured data shown in Figure 2.0-2. The fact that the adverse effect of overlapping channels can be reproduced in simulation provides strong indication that it is not due to the particular radio implementation used to generate the measured data described in Section 2, but rather is a fundamental byproduct of overlapping channels.

5.0 Differential Phase Distortion

The adverse effects of using overlapped FHSS channels was described in the previous section. However, reproducing the effects in simulation does not provide an underlying explanation. Analysis has shown that the increase in susceptibility to interference is proportional to the offset in the center frequency of the interfering signal. Referring to Figure 4.0-1, as the offset increases, so do the adverse effects of the interfering signal.

As the frequency separation exceeds about 60% of a channel width (about 3 MHz), this situation reverses itself. At this point, the IF and post detection filters begin to roll off more quickly, thereby rejecting more of the interference. Beyond this point, as frequency separation between the desired and interfering signals continues to increase, the filter effects begin to dominate and the receiver is tolerant of much higher levels of interference.

5.1 Borrowing from FM Noise Theory

As it turns out, the influence of frequency offset on the severity of an interfering signal should come as no surprise. The effect of noise (or interference) frequency offset on FM demodulation has long been known. It can be shown that the noise spectral density (S_n) at the output of an FM demodulator is proportional to the square of frequency offset (f):

$$S_n = (N_0 / A_c^2)\ f^2 \tag{4}$$

where N_0 = noise density
A_c = Signal Power

In this case, both A_c and N_0 are constants. Therefore the Sn is entirely dependent on frequency offset (f) as shown in Figure 5.1-1. The interaction of noise and a signal in an FM system is closely related to the interaction of a desired signal (S) and an interfering signal (I) as described in the following section.

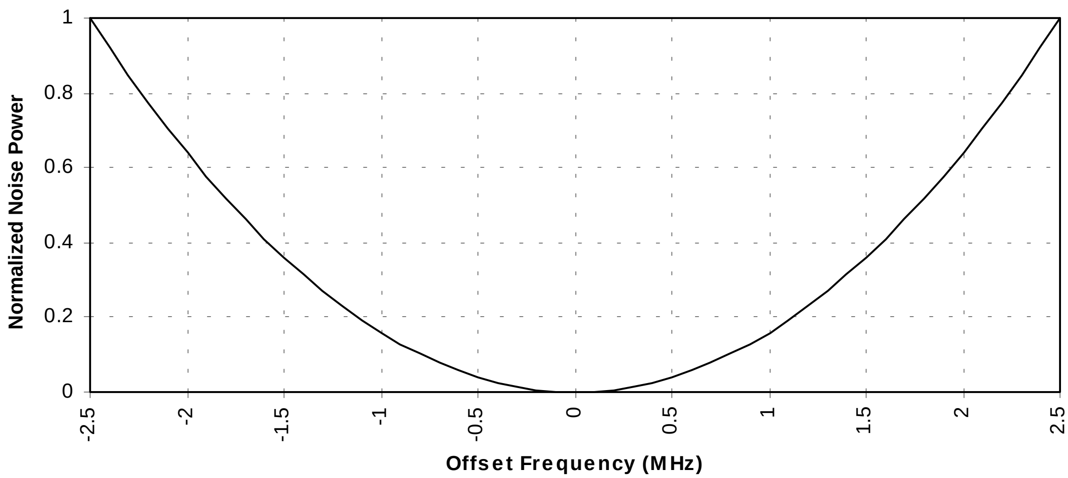


Figure 5.1-1 Noise Spectral Density at Output of an FM Demodulator

5.2 Vector Analysis

This section is intended to convey a simple, but completely accurate explanation of the underlying properties of a limiter/discriminator receiver which result in the enhancement of interference from partially overlapping channels. The underlying cause of the effect described above is differential phase distortion which occurs when the desired and interfering signals are demodulated. This can be explained via vector analysis of the combined desired and interfering signals. Three separate cases are treated:

A. Signal (S) and Interference (I) have the same instantaneous frequency
B. Signal (S) and Interference (I) have a small frequency offset
C. Signal (S) and Interference (I) have a larger frequency offset

For Case A, no interference results regardless of the relative phase of vectors S and I. However, when a frequency offset is present (Case B), a differential phase distortion occurs. This distortion becomes worse as frequency offset increases (Case C). Finally, these results are treated quantitatively. The dependence of interference power at the discriminator output is shown to be dependent on the square of frequency offset. Differential phase distortion cannot be eliminated and is the root cause of the increased susceptibility of the receiver to interference from an overlapped channel.

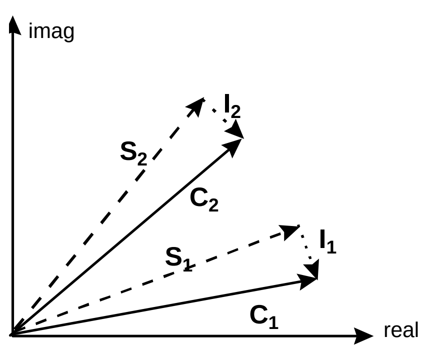


Figure 5.2-1a

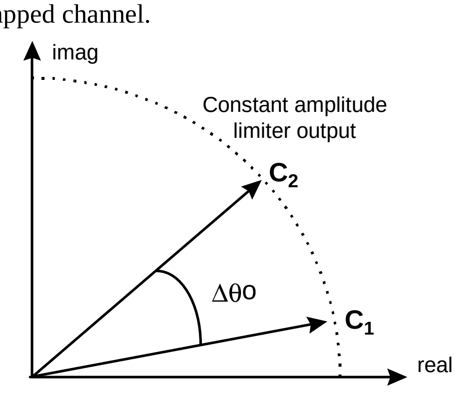


Figure 5.2-1b

Figure 5.2-1 Case A: Interference at Same Frequency as Desired Signal

Figure 5.2-1a shows consecutive samples of the received signal at the discriminator output with the interfering and desired signals at the same instantaneous frequency. The sample rate is much higher than the symbol rate. Note that the limiter output is a constant amplitude signal. The discriminator output is a voltage which is proportional to the instantaneous frequency ($d\theta/dt$) of the received signal. For a fixed sample rate, *dt* is constant. The demodulated signal voltage is proportional to $\Delta\theta_0$, shown in Figure 5.2-1b.

As mentioned above, amplitude distortion is eliminated by the limiter. Further, when the instantaneous frequency of the two signals is the same, the relative phase of the desired signal vector (S) and the interference vector (I) remain the same from sample to sample. Therefore, the phase error is identical for the two successive composite vectors (C_1 and C_2). Since the output of the discriminator is proportional to $\Delta\theta$, no *differential phase distortion* occurs, regardless of the relative amplitude and phase of vectors I and S.

This situation is illuminating, but in practice both the desired and undesired signals are frequency modulated. Even with co-channel interference, there is some minimal frequency offset between the desired and undesired signal. In this situation, the interfering signal vector is typically at a slightly different frequency than the desired signal. As shown in Figure 5.2-2, the phase of the interference vector (I_S) is changing slowly relative to the desired signal vector (S).

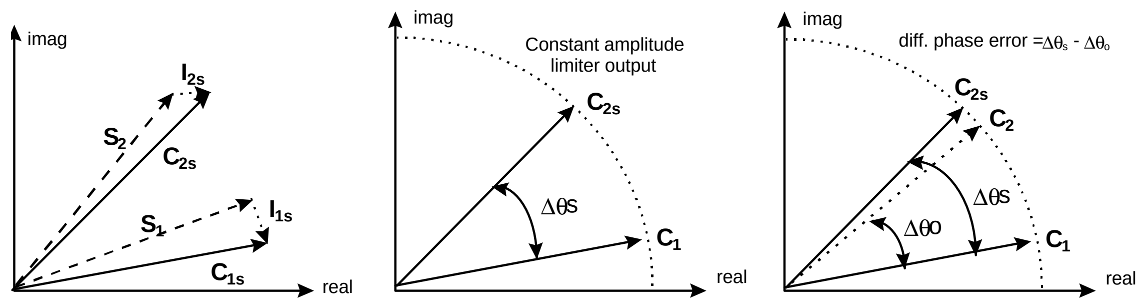


Fig. 5.2-2a *Fig. 5.2-2b* *Fig. 5.2-2c*

Figure 5.2-2 Case B: Demodulation with Small Frequency Offset Between Desired (S) and Interfering (I) Signals

Note from Figure 5.2-2c, the phase error is non-zero. This induces an error in the instantaneous output voltage of the discriminator. As will be demonstrated in a subsequent section, this in turn causes the eye diagram to begin to close. This is closely analogous to the situation of co-channel interference. Instantaneous frequency offsets are not zero, but are *minimized* for CCI. This explains why the receiver is more tolerant of co-channel interference than to interference from a partially overlapped channel.

As the frequency difference between the desired and interfering signals increases, the phase rotation of the vector I_F is much faster than the desired signal vector (S). Therefore, the relative phase of the two vectors is much greater between samples. Referring to Figure 5.2-3, this translates directly into a greater phase differential error at the discriminator input.

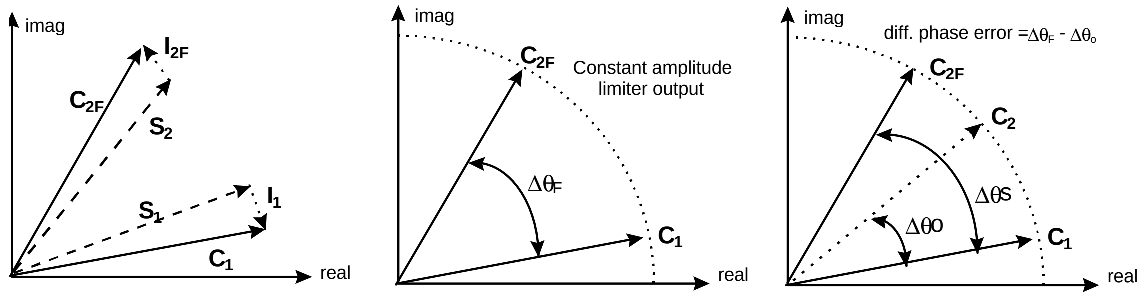


Fig. 5.2-3a *Fig. 5.2-3b* *Fig. 5.2-3c*

Figure 5.2-3 Case C: Demodulation with Larger Frequency Offset Between Desired (S) and Interfering (I) Signals

5.2.1 Quantitative Treatment

From the preceding discussion, it is apparent that frequency distortion is dependent upon the rotation of the interference vector (I) relative to the signal vector (S), as shown in Figure 5.2.1-1 below.

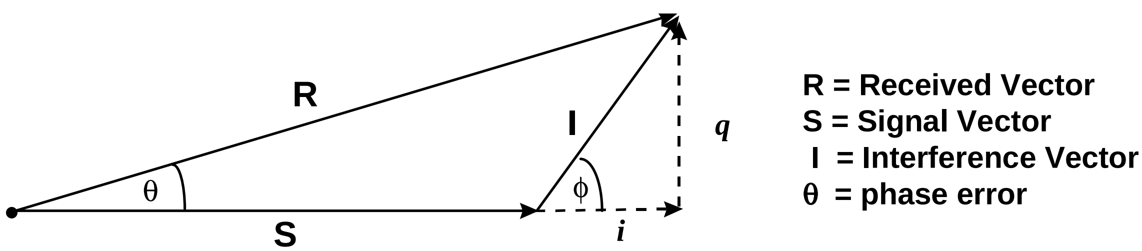


Figure 5.2.1-1 Interference Results in Phase and Frequency Errors

Rate of rotation of interference vector (I) relative to signal vector (S) is equal to frequency offset (Δf) between desired signal and interference:

$$\omega = 2\pi\Delta f$$

$$i = \mathrm{I}\cos(\omega t)$$

$$q = \mathrm{I}\sin(\omega t)$$

$$\phi = \omega t$$

In order to facilitate analysis, vector amplitudes are normalized to the amplitude of the interference vector (I). In this manner, signal vector (S) is expressed in terms of S/I, or Signal-to-Interference Ratio (Σ):

$$\mathrm{I} = 1.0$$

$$\mathrm{S} = \mathrm{S/I} = \Sigma \qquad \text{(where } \Sigma = \text{SIR)}$$

$$i = \cos(\omega t)$$

$$q = \sin(\omega t)$$

θ = instantaneous phase error

$d\theta/dt$ = instantaneous frequency error

From Figure 5.2.1-1:

$$\textit{Phase Error} = \theta = \tan^{-1}\left[\frac{q}{\Sigma + i}\right] = \tan^{-1}\left[\frac{\sin(\omega t)}{\Sigma + \cos(\omega t)}\right] \quad (5)$$

$$\textit{Frequency Error} = d\theta/dt = \left[\frac{\omega\left(\Sigma\cos(\omega t) + 1\right)}{\Sigma^2 + 2\Sigma\cos(\omega t) + 1}\right] \quad (6)$$

Note from Equation (6) that $d\theta/dt$ is directly proportional to ω, and by extension to frequency offset (Δf). The error voltage at the discriminator output (V_{error}) is therefore also directly proportional to Δf, and interference power (P_{error}) is proportional to the square of frequency offset (Δf^2) :

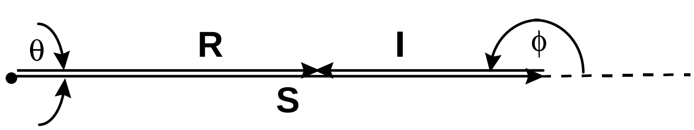
$$d\theta/dt \approx \omega = 2\pi\Delta f$$

$$\therefore \quad V_{error} \approx \Delta f$$

$$\Rightarrow \quad P_{error} \approx \Delta f^2$$

The second order derivative of θ ($d^2\theta/dt^2$) is computed to determine where frequency error is maximized:

$$d^2\theta/dt^2 = \left[\frac{\Sigma\omega^2\,\sin(\omega t)\left[1 - \Sigma^2\right]}{\left[\Sigma^2 + 2\Sigma\cos(\omega t) + 1\right]^2}\right] \quad (7)$$



R = Received Vector
S = Signal Vector
I = Interference Vector
$\phi = \pi$
θ (phase error) = 0
$d\theta/dt$ (freq error) is maximized

Figure 5.2.1-2 Interference Effect is Maximized for $\phi = \pi$ (Phase Error = 0, Freq Error is Maximized)

Note that $d^2\theta/dt^2$ for $\omega t = \phi = 0, \pi$. However $|d\theta/dt|$ is maximized at $\omega t = \phi = \pi$. Referring to Figure 5.2.1-2, the signal vector (S) and interference vector (I) are in anti-phase at this point. At this point, there is no phase error, but frequency error is maximized. In addition, as a result of the destructive interference of vectors S and I, the received vector (R) is at the minimum value.

For FM systems, noise voltage at the discriminator output is not independent of the received signal strength. In fact, noise voltage is inversely proportional to the received signal amplitude. This is significant because effect of thermal noise is maximized at precisely the same point that interference effects are also maximized. Thus the adverse effects of overlapping channels are compounded. These effects are in no way “implementation-dependent”, but rather are an unavoidable consequence of allowing FM channels to overlap.

5.3 A Graphic Example

The main objective of this section is to demonstrate the validity of the explanation put forward for the interference enhancing effect of partially overlapped FHSS channels. A review of the measured receiver desensitization data of Figure 2.0-2 is helpful at this point. Starting from 0 MHz frequency offset between the interfering and desired signals (CCI), the receiver becomes increasingly susceptible to interference as frequency separation is increased. This trend continues until about a 0.6 channel width separation is reached, at which point this trend is reversed. Beyond this point, the receiver is able to provide reliable operation in the presence of increasing levels of interference.

According to the explanation put forward in this paper, there are two main forces at work:

1. An FM demodulator enhances the effects of noise and interference in proportion to the square of frequency separation from the desired signal. This is the main reason why WBFH receiver desensitization performance will degrade between between 0 MHz offset and roughly 3 MHz offset (0.6 channel widths).
2. Beyond 0.6 channels widths of frequency separation, receiver desensitization performance continuously improves. This occurs because the interfering signal now begins to extend beyond the passband of the receiver. The interfering signal becomes increasingly suppressed by the receiver filtering. By the time frequency offset reaches 5 MHz (ACI), the effect of the receiver filtering begins to dominate. Receiver desense performance improves quite rapidly as frequency separation is further increased. Note that receiver desense is worse than either CCI or ACI for all partially overlapping channels (1 MHz $\leq$ freq. offset $\leq$ 4 MHz).

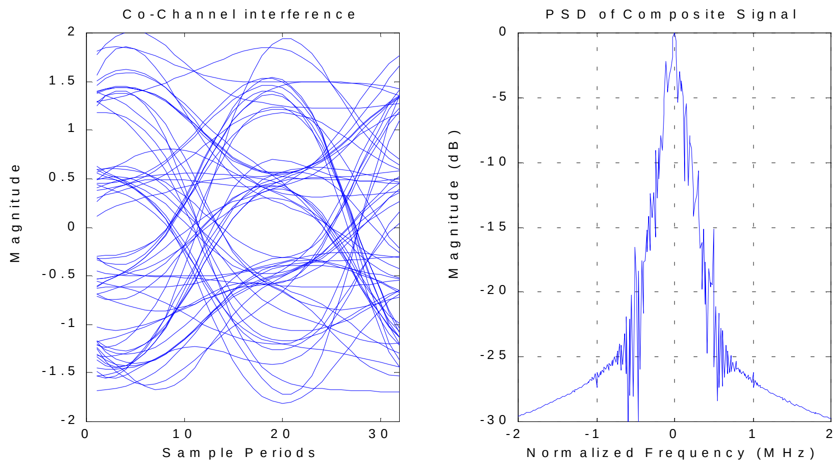
In order to demonstrate the validity of this explanation, simulations have been run with the receiver filtering removed and thermal noise eliminated. This enables study of the effect of frequency offset in isolation. AWGN was not added to the composite received signal because noise effects would have dominated performance with the IF and post-detection filters removed.

The interfering signal level was increased until a BER of 10^{-3} was reached for the co-channel case. With the signal-to-interference level held constant at this level, the frequency offset was increased in 1 MHz increments. BER was measured at each point. According to the explanation above, the BER should increase as frequency separation increased. Further, as frequency separation increases beyond 3 MHz (0.6 channel widths), BER *should continue to increase* since there is no filter present to suppress interference which has large frequency offsets. As shown in Table 5.3-1, simulation results behave exactly as predicted.

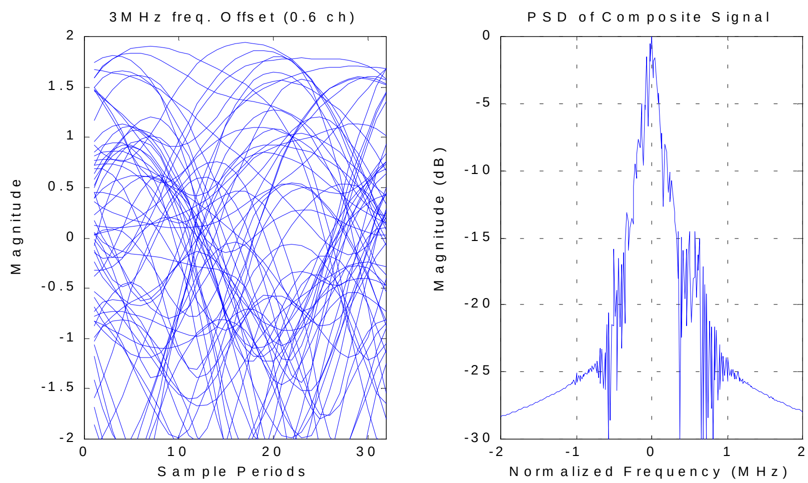
Offset	**BER**
0 MHz (CCI)	1×10^{-3}
1 MHz	1.6×10^{-2}
2 MHz	5.7×10^{-2}
3 MHz	0.136
4 MHz	0.193
5 MHz (ACI)	0.264

Table 5.3-1 BER vs. Δf with Receiver Filters Removed (constant SIR)

The influence of frequency offset can be shown graphically by examining the impact on the eye diagram. Figure 5.3-1 shows the simulated composite PSD and eye diagram for the case of CCI with receiver filtering removed, thermal noise turned off, and SIR held constant (17 dB). Composite signal PSD's and eye diagrams for 3 MHz and 5 MHz frequency offsets are shown in Figures 5.3-2 and 5.3-2 respectively. Note the progressive deterioration of the eye diagram as frequency separation is increased.



<u>Figure 5.3-1 Composite PSD and Eye Diagram for 0 MHz (CCI) Frequency Offset with Rx Filtering Removed</u>



<u>Figure 5.3-2 Composite PSD and Eye Diagram for 3 MHz Frequency Offset with Rx Filtering Removed</u>

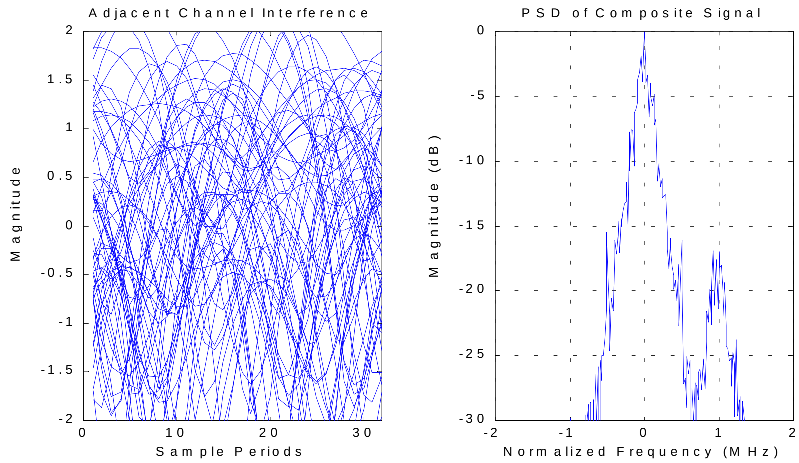


Figure 5.3-3 Composite PSD and Eye Diagram for 5 MHz (ACI) Frequency Offset with Rx Filtering Removed

The results presented in this section provide further evidence that the effects of frequency offset between the desired and interfering signals on WBFH receivers having limiter/discriminator architectures are thoroughly understood. Further, the adverse effects described are an unavoidable consequence of using overlapped WBFH channels as recommended by the HomeRF Working Group.

6.0 System Considerations

The results in the preceding sections have demonstrated that interference from partially overlapped channels is more severe than either CCI or ACI. The following paragraphs explore the consequences of this result from a system perspective. The particular issues addressed are:

a. rate of collisions among WBFH systems
b. adverse impact on Clear Channel Assessment (CCA) mechanisms

The overall effect of increased collision rates and impaired CCA mechanisms is more frequent dropped packets and the accompanying retransmissions. This type of operation conflicts directly with the goal of promoting efficient use of the spectrum.

6.1 Rate of Collisions

Referring to Figure 4.0-1, it can be seen that interference from partially overlapping channels is worse than either ACI or CCI. Taking the receiver desensitization for CCI (- 18.4 dB) as the threshold, there are a total of 9 channels which suffer either equal or greater levels of interference. Therefore, the odds of exceeding this threshold of interference on any given hop is 12%, or nine channels out of seventy five.

To provide some point of reference, conventional FHSS would suffer from collisions of this severity on at most three channels. The rate of collision would therefore be about 4% (3/75). There are some conventional FHSS systems which do even better. Bluetooth radios are designed to withstand ACI of up to 0 dB. Therefore, they are only susceptible to significant levels of interference from any interfering signal below 0 dB (relative to the desired signal) on one channel, resulting in a collision rate of 1.2%.

It must be pointed out that selecting an interference threshold is a rather subjective exercise. The level of susceptibility of any system is highly dependent on the IF filter characteristics. IF filters used in these simulations have fairly steep roll off characteristics, and are better than those used on most FHSS systems on the market today. In fact, many consumer oriented products use very broad IF filters. These types of radios would suffer *much* higher levels of interference because of the inability to reject interference which has significant frequency offset from the desired signal. As shown in Figure 5.1-1, the impact of noise or interference increases as the square of frequency offset.

6.2 Adverse Impact on Collision Avoidance Mechanisms

Relatively sophisticated collision avoidance mechanisms are employed in many wireless LAN (WLAN) systems sold today. These measures are commonly referred to as Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA). Systems employing these measures typically perform Clear Channel Assessment (CCA) to determine if the medium is busy prior to transmission.

When a receive energy threshold is exceeded, CSMA receivers go into a signal acquisition mode. At this point, it is unknown whether the received energy is due to an incoming packet, a packet addressed to another node, or to interference. While in acquisition mode, the receiver attempts to demodulate the signal and determine destination address of the packet. However, systems employing WBFH will not be capable of demodulating another WBFH signal on a partially overlapping channel due to the carrier offset (at least 1 MHz). Therefore, the effectiveness of the CSMA/CA mechanism is severely impaired on precisely those channels for which the interference level is most severe.

6.3 Other Waveforms

Up to this point, the discussion has focused entirely on the impact of overlapped channels on receivers with limiter/discriminator architectures. This is for good reason, since commercially available FHSS systems use this receiver architecture almost without exception. These systems include:

a. HomeRF (SWAP-CA)
b. IEEE 802.11 FHSS
c. Bluetooth
d. Symphony
e. HomeFree

As mentioned above, HomeRF has made specific reference to their intention to use FSK modulation for WBFH applications [2]. In order to deliver the spectral efficiencies described by HomeRF (2 bits/sec/Hz) in their letter to OET of November 11, 1998, 4FSK will be required. The spectral efficiency of any form of FSK modulation is dependent upon the modulation index (h):

h = frequency deviation between symbols / symbol rate

In order to deliver 2 bits/sec/Hz, 4FSK systems employ modulation indexes of about 0.15, which is very sub-optimal in terms of Eb/No (required very high SNR for reliable signaling) and in terms of performance in multipath.

However, there is no requirement in either the current or proposed rules requiring the use of any particular form of modulation. There are many other forms of modulation to choose from, but most will not deliver a spectral efficiency of 2 bits/sec/Hz. Various modulation schemes and the respective spectral efficiencies (based on bandwidth between first nulls) are summarized in Table 6.3-1.

Waveform	Spectral Efficiency (bits/sec/Hz)
BPSK	0.5
MSK	0.75
QPSK	1.0
4FSK (h = 0.15)	2.0
16QAM	2.0

Table 6.3-1 Spectral Efficiencies of Common Waveforms

This list is not exhaustive and spectral efficiency can be improved by filtering the transmitted signal, but it does demonstrate that the many waveforms, and particularly those found in the types of consumer devices referenced by HomeRF, are not capable of 2 bits/sec/Hz in a practical sense. In order to make good on claimed data rates for WBFH 16QAM might be used.

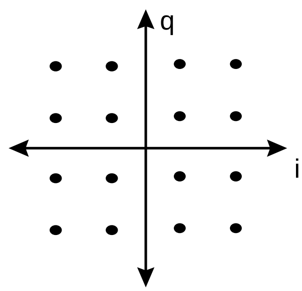


Figure 6.3-1 Signal Constellation for 16 QAM

The signal constellation for 16 QAM is shown in Figure 6.3-1. 16 QAM is a far more complex waveform than 4FSK. Note that the information is contained in both the amplitude and phase of the received signal. 16 QAM therefore requires linear demodulation. Although these considerations would certainly drive cost, they would not, by themselves, render 16 QAM unsuitable for WBFH applications. But unlike 4FSK, a complex waveform such as 16QAM is susceptible to both phase and amplitude distortion. It is therefore entirely reasonable to assume that the effects of overlapping channels will be even worse for complex waveforms such as 16QAM than for 4FSK.

7.0 Conclusions

Measured test data from FHSS radios has demonstrated that interference from partially overlapped channels represents a "worst case" situation for limiter/discriminator receivers. This effect has been reproduced in simulation and has been shown to be the result of a well known property of FM receivers which enhances the effects of noise and interference in proportion to the square of frequency separation from the desired signal. It has also been shown that increased levels of interference are the inevitable consequence of using overlapping channels for WBFH applications.

As a result of the interference described above, the collision rate among WBFH systems will be increased. This in turn will result in numerous packet retransmissions, thereby increasing interference to other users. Another consequence of overlapping WBFH channels will be the reduced effectiveness of collision avoidance mechanisms such as CSMA/CA. These "listen-before-talk" collision avoidance measures typically rely on sensing the carrier signal of other users in order to make a clear channel assessment Due to the large DC offsets, it will be extremely unlikely that the carrier of a partially overlapped interferor could be demodulated. Clear channel assessment would therefore be reduced to reliance on simple energy detection, witch is a far less robust method.

This paper focused mainly on the impact of overlapping FHSS channels on FSK receivers. This is entirely appropriate because this radio type is used almost exclusively in current FHSS systems. However, as described above, it is reasonable to assume that the effects of overlapping WBFH channels will be as bad or worse for other waveforms capable of delivering 2 bits/sec/Hz as claimed by HomeRF in their petition to the FCC in this matter.

It is commendable that OET gives serious consideration to petitions for rule making from industry in order to provide consumers with better services and more choices in the marketplace. However, petitions from industry should also be backed up by rigorous engineering analysis which demonstrates the valid basis of claimed benefits. In fact, there are several technical flaws with the WBFH rule changes proposed by HomeRF, the use of overlapping channels being just one example. Based on these technical shortcomings, the proposed changes to Section 15.247 of the Commission's Rules to accommodate WBFH should be rejected.

References

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